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Research article

The influence of market factors on the potential environmental benefits of the recycling of rare earth elements

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Supplementary

S1. Identification of determining co-products of REE deposits

As REEs are always produced as co-products of one another, a change in the mining output of one element results in the co-production of other REEs that affects other production systems in turn. This section provides an analysis of the determining co-product of the deposits that produce REEs as the primary output of the mining activity, as well as the subsequent identification of the marginal supplier.

In the period 2013–2016, REEs were the primary output of the Mountain Pass mine in California, of mines in Sichuan, and the ion adsorption-type ores in China. Also the Mt. Weld, Yangibana and John Galt deposits in Australia (have the potential to) produce REEs as the main product [1,2]. The revenue for each mine is calculated by the REE content of the mine and the market prices of the rare earth oxides (REOs) in 2013 [3]. The marginal production costs are estimated to be 80% of the total revenue [4,5]. The determining co-product is one of the products that must be produced to cover the marginal production costs and which has the lowest normalized market trend [6].

Table S1 summarizes the market information on which the calculation of the determining co-product is based.

Table S2–S8 show the characteristics of the deposits in which REEs can be produced as a determining co-product. Based on these characteristics, the determining co-product of each mine is calculated. Table S9 shows the REE that is identified as the determining co-product of the abovementioned deposits.

The increased demand for the REEs that are produced as determining co-products is modeled by the additional production from their marginal supplier. The Longnan and the Southeast Guangdong deposits are the only currently operating deposits that produce yttrium and dysprosium as determining co-product, respectively. Therefore, these deposits can be identified as their marginal suppliers. Among the mines that produce neodymium as a determining co-product, the marginal supplier is the producer that has the lowest long-term operation costs [7,8]. The marginal supplier could also be a mix of these producers. More knowledge on the characteristics of each mine is necessary to identify the marginal supplier in a systematic way. The identification of the marginal supplier influences the inventory related to the mining activity, as well as the composition of the deposit, hence the production of co-products. Due to the fact that the Yangibana deposit is not in operation at the time of analysis and the fact that the Mount Weld deposit is not profitable (as mentioned in the paper), it is assumed that the Xunwu mine is the most cost-competitive producer of neodymium, and therefore its marginal supplier.

Table S1. Market information of REEs.

REE	Market prices 2013 (USD/kg) [3]	Market trend [9]
Lanthanum	7.866	6%
Cerium	7.863	6%
Praseodymium	91.4	6%
Neodymium	71.8	7%
Samarium	13.3	10%
Europium	1095	8%
Gadolinium	24	9%
Terbium	920	8%
Dysprosium	555	9%
Holmium	66	8%
Erbium	68	6%
Thulium	53*	8%
Ytterbium	53	8%
Lutetium	1201	8%
Yttrium	26	8%

*Assumption: same market price as ytterbium, as both are co-products from the same extraction activity.

Table S2. Characteristics of the Mountain Pass deposit.

Mountain Pass, US	Concentration (%) [10]	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	0.1	0.03	80.0
Lanthanum	33.2	2.61	0.2
Cerium	49.1	3.86	0.1
Praseodymium	4.34	3.97	1.4
Neodymium	12	8.62	0.6
Samarium	0.8	0.11	12.5
Europium	0.1	1.10	80.0
Gadolinium	0.2	0.05	45.0
Terbium	trace	-	-
Dysprosium	trace	-	-
Holmium	trace	-	-
Erbium	trace	-	-
Thulium	trace	-	-
Ytterbium	trace	-	-
Lutetium	trace	-	-

Table S3. Characteristics of the Xunwu deposit.

Xunwu, Jiangxi, China	Concentration (%) [10]	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	8	2.1	1.0
Lanthanum	43.4	3.4	0.1
Cerium	2.4	0.2	2.5
Praseodymium	9	8.2	0.7
Neodymium	31.7	22.8	0.2
Samarium	3.9	0.5	2.6
Europium	0.5	5.5	16.0
Gadolinium	3	0.7	3.0
Terbium	trace	-	-
Dysprosium	trace	-	-
Holmium	trace	-	-
Erbium	trace	-	-
Thulium	trace	-	-
Ytterbium	0.3	0.2	26.7
Lutetium	0.1	1.2	80.0

Table S4. Characteristics of the Longnan deposit.

Longnan, Jiangxi, China	Concentration (%) [10]	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	65	16.90	0.12
Lanthanum	1.82	0.14	3.02
Cerium	0.4	0.03	15.00
Praseodymium	0.7	0.64	8.57
Neodymium	3	2.15	2.33
Samarium	2.8	0.37	3.57
Europium	0.1	1.10	80.00
Gadolinium	6.9	1.66	1.30
Terbium	1.3	11.96	6.15
Dysprosium	6.7	37.19	1.34
Holmium	1.6	1.06	5.00
Erbium	4.9	3.33	1.22
Thulium	0.7	0.37	11.43
Ytterbium	2.5	1.33	3.20
Lutetium	0.4	4.80	20.00

Table S5. Characteristics of the Southeast Guangdong deposit.

Southeast Guangdong, China	Concentration (%) [10]	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	59.3	15.42	0.1
Lanthanum	1.2	0.09	4.6
Cerium	3	0.24	2.0
Praseodymium	0.6	0.55	10.0
Neodymium	3.5	2.51	2.0
Samarium	2.2	0.29	4.5
Europium	0.2	2.19	40.0
Gadolinium	5	1.20	1.8
Terbium	1.2	11.04	6.7
Dysprosium	9.1	50.51	1.0
Holmium	2.6	1.72	3.1
Erbium	5.6	3.81	1.1
Thulium	1.3	0.69	6.2
Ytterbium	6	3.18	1.3
Lutetium	1.8	21.62	4.4

Table S6. Characteristics of the Yangibana deposit.

Yangibana, Australia	Concentration (%) [11]	Revenue (USD/kg of ore)	Normalized market trend
Neodymium	76%	54.9	0.09
Praseodymium	20%	18.4	0.30
Europium	2%	22.7	3.86
Dysprosium	1%	7.4	6.77

Table S7. Characteristics of the John Galt deposit.

John Galt, Australia	Concentration (%) [12]	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	66.77	17.36	0.12
Lanthanum	0.46	0.04	11.96
Cerium[a]			
Praseodymium[a]			
Neodymium[a]			
Samarium	1.25	0.17	8.00
Europium	0.4	4.38	20.00
Gadolinium	4.57	1.10	1.97
Terbium	1.18	10.86	6.78
Dysprosium	9.34	51.84	0.96
Erbium	7.12	4.84	0.84
Ytterbium	5.8	3.07	1.38
Holmium	3.12	2.06	2.56
Thulium[b]			
Lutetium[b]			

[a]Based on lanthanum; [b]Based on holmium.

Table S8. Characteristics of the Mount Weld deposit.

Mount Weld, Australia	Concentration (%) [10]	Revenue (USD/kg of ore)	Normalized market trend
Yttrium	trace		
Lanthanum	26	2.05	0.2
Cerium	51	4.01	0.1
Praseodymium	4	3.66	1.5
Neodymium	15	10.77	0.5
Samarium	1.8	0.24	5.6
Europium	0.4	4.38	20.0
Gadolinium	1	0.24	9.0
Terbium	0.1	0.92	80.0
Dysprosium	0.2	1.11	45.0
Holmium	0.1	0.07	80.0
Erbium	0.2	0.14	30.0
Thulium	trace	-	-
Ytterbium	0.1	0.05	80.0
Lutetium	trace	-	-

Table S9. Determining co-product of REE mining from mines that produce REEs as the main output.

Mine	Status of operation (2013–2016)	Determining co-product
Mountain Pass, US	Shut down [13]	Lanthanum
Xunwu, Jiangxi, China	Operating	Neodymium
Longnan, Jiangxi, China	Operating	Yttrium[a]
Southeast Guangdong, China	Operating	Dysprosium
Yangibana, Australia	Start production 2018 [11]	Neodymium
John Galt, Australia	Exploration [14]	Dysprosium
Mount Weld, Australia	Operating	Neodymium[b]

[a]If marginal operating costs are 79.6% of the revenue, erbium is the determining co-product.

[b]With the assumption that the marginal operating costs are 80% of the revenue, lanthanum is the determining co-product. The determining co-product is neodymium if the marginal operating costs are 78% of the total revenue. The mining company highlights that NdPr is their most significant product and that prices for NdPr have remained low [15]. Neodymium is chosen here due to the expected increase in price compared to the relatively stable price for lanthanum [16,17]. Considering the fact that the mine is not yet profitable [15], the revenue of all elements is currently required. Although currently there is a small surplus of neodymium, the market is expected to stay tight and the material has been identified as critical [18], while the surplus for lanthanum is expected to increase [9]. Among the critical elements of the mine, neodymium has the lowest normalized market trend. Therefore, neodymium is considered to be the determining co-product of the Mount Weld deposit.

S2. Modeling of the REE separation steps

The REEs are separated from each other in different separation steps which take place in different reactors. We identify first which separation steps are part of the primary production route of REEs, and which separation steps could be considered as "valorization activities" from materials supplied by storage. The order of separation often follows Figure S1 [19–21]. If the rare earth concentrate contains mostly light rare earths (LREE), the focus will be put on the left-hand side of the figure, while heavy rare earths (HREE) are mainly extracted in the separation activities on the right-hand side of the figure. However, the exact sequence of separation depends on the composition of the rare earth concentrate. If a separation activity delivers only REEs of which there is a surplus—for example, lanthanum and cerium—the elements could be stored as unseparated elements.

Due to lack of detailed information with regard to the separation activity, it is assumed that separation takes place if the REE mix contains at least one element that is not being stored. Elements are assumed to be stored in their unseparated form if all elements are being stored (and have a value of $A = 0$). Therefore, for example, the increased demand for lanthanum or cerium might be provided from storage, although it would require the separation of La/Ce. Whether this separation activity is triggered by the demand for lanthanum or cerium can be identified by the calculation of the determining co-product of this specific activity. The assumption is done that the revenue of either co-product is sufficient to separate La/Ce. Lanthanum has the highest normalized market trend in the La/Ce mix from Bayan Obo, which is expected to be the largest contributor to the La/Ce storage. This makes lanthanum the determining co-product of this separation activity. Hence, the dataset of primary lanthanum contains inventory related to the separation of lanthanum and cerium. The additional consumption of primary cerium does not lead to additional impacts, except, for example, impacts related to transport.

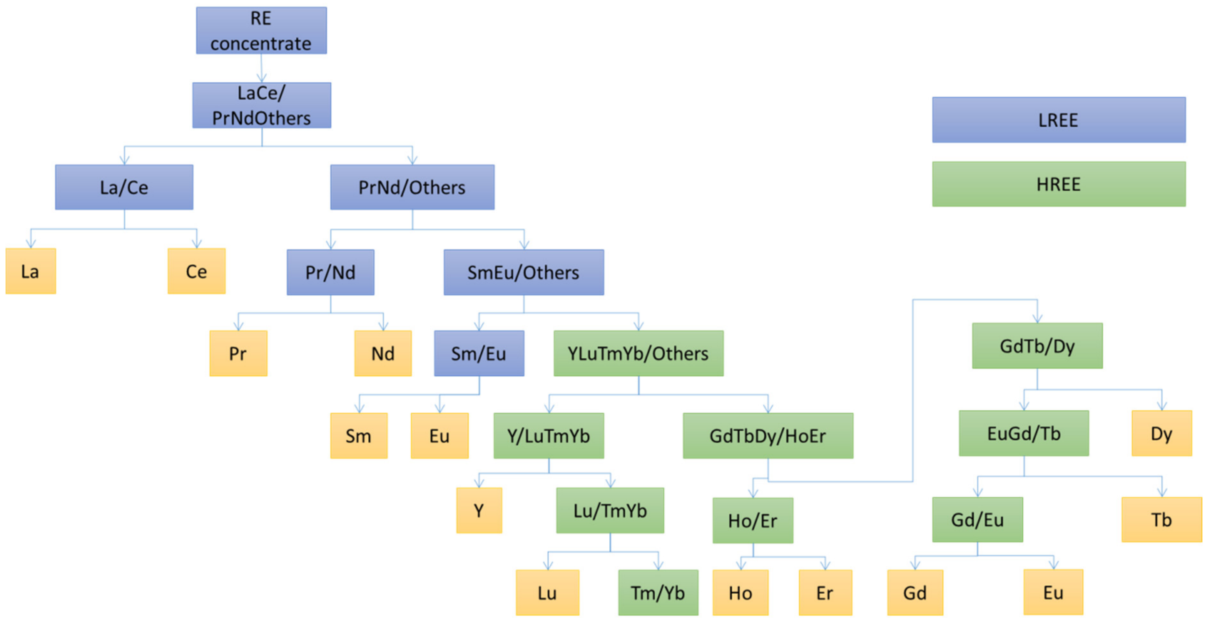

Figure S1. Separation process of REEs [19,20]. The content of the REE mix determines whether the emphasis is put on the LREE or the HREE separation route.

S3. Terbium

Terbium is—similarly to europium—mainly used within phosphors, so the same reflection as for europium could be relevant [9]. Terbium is also used in permanent magnets, where it can displace dysprosium and vice versa [22]. In that case, the additional production of terbium might displace the primary mining of dysprosium. [22] states that dysprosium is not often displaced by terbium due to the important application of terbium in phosphors. In that case, the indirect effects due to the additional production or consumption of terbium are the same as of europium. However, Binnemans also states that the application of terbium in magnets may become more relevant when fluorescent lamps will be more and more displaced by LED lights [22]. The European Commission is not conclusive about the current market situation of terbium [9]. Binnemans mentions that terbium can, at the time of his writing, be supplied from storage [22]. Therefore, also for the marginal user of terbium, multiple scenarios are possible. Fluorescent lamps could be considered as the marginal user, which would make the dataset of terbium very similar to the dataset of europium. When fluorescent lamps are becoming superfluous due to the implementation of LED lights, terbium could substitute dysprosium or be supplied from storage. To show the consequences of divergent situations, we assume that terbium displaces dysprosium in a 1:1 mass ratio and no downstream effects take place. This assumption is highly uncertain and could be verified with price elasticities of demand (to identify the marginal user) and cross-price elasticities (to identify good substitutes) [23]. Unfortunately, price elasticities are not available for all materials in all applications. Scenario analyses—such as done for europium—could confirm the sensitivity of this assumption.

S4. LCI of CFL, LED, and Halogen lamps

For the LCI of Scenarios 1 and 2 of europium, the full life cycles of a compact fluorescent lamp (CFL), LED lamp, and halogen lamp need to be modeled. The inventory used in the study is largely based on [24]. Some modifications were needed to be made, which are explained in the following sections.

Scholand and Dillon [24] conducted LCA studies on 4 different lamps: incandescent lamps, CFLs, LED for the year 2012, and LED for the year 2017. Unfortunately, no inventory data is provided for halogen lamps. As this study provides the most detailed information for the largest number of types of lamps, we decided to use the LCI of incandescent lamps as a proxy for the LCI of halogen lamps. Only the use phase of the incandescent lamp is adapted according to the performance parameters of the halogen lamp (Table S10). With regard to the two LED lamps, we only used the inventory for LED for the year 2017, as this is considered to be the most up-to-date estimate. The functional output of the lamps that is used as basis for comparison is the "total lifetime light output". This means that one would need 29 halogen lamps, 5 CFLs, or 1 LED (2017) in order to have the same output of light. Scholand and Dillon used the database ecoinvent 2.2. We modified the original processes to datasets of the consequential system model of ecoinvent 3.7.1.

Table S10. Performance parameters for different types of lamps.

	Incandescent [24]	Fluorescent [24]	LED 2012 [24]	LED 2017 [24]	Halogen [25]
Power consumption (watt)	60	15	12.5	6.1	43
Lumen output (lumens)	900	825	812	824	750
Efficacy (lm/W)	15	55	65	134	17
Lamp lifetime (hours)	1500	8000	25000	40000	1500[a]
Total lifetime light output (Mlm-hr)	1.35	6.6	20.3	33	1.125
Scaling factor	4.9	1	0.3	0.2	5.9

[a]This number is adapted to make the lifetime the same for incandescent lamps, which is the case in [25]

LCI and impact assessment of a LED lamp

The following adaptations have been made to the inventory of an LED lamp as described by [24].

Three-inch sapphire wafer manufacturing (per wafer)

- The ecoinvent dataset for zeolite could not be adjusted—as suggested by Scholand and Dillon, due to the fact that the dataset is aggregated.

LED die fabrication (per wafer)

- AuSn solder: Gold {GLO}| market for | Conseq, S

- Energy: Electricity, medium voltage {CN}| market group for | Conseq, S
- Target Al and TMAl: Aluminium, primary, liquid {GLO}| market for | Conseq, S
- Target W: Palladium {GLO}| market for | Conseq, S

LED packaging assembly (per LED)

- Added: three-inch sapphire wafer manufacturing: 1/3250 p
- Added: LED die fabrication: 1/3250 p
- ESD diode: Diode, glass-, for surface-mounting {GLO}| market for | Conseq, S
- Gold: Gold {GLO}| market for | Conseq, S

LED lamp

- Remote phosphor:
    - o Yttrium oxide (from Longnan): 450 mg [26]
    - o Aluminium hydroxide {GLO}| market for | Conseq, S: 550 mg (estimated from [27])
    - o Cerium oxide (from storage): 0.7 mg [26]
- Plastic phosphor host: Polypropylene, granulate {GLO}| market for | Conseq, S
- Inductor: Inductor, auxilliaries and energy use {GLO}| production | Conseq, S: 3 g
- Capacitor SMD: 0.688 g (average weight of 0.086 g)
- Electrolytic capacitor: 5.11 g (average weight of 1.29 g)
- Diode: 127 mg (average weight of 32 mg)
- Resistor SMD: 226 mg (average weight of 9.8 mg)
- Resistor: 7.52 g (average weight of 3.8 g)
- Transistor: 25.1 g (average weight of 6.34 g)

LED packaging and transport

- Packaging: Corrugated board box {ROW}| market for corrugated board box | Conseq, S
- Transport sea: 20.000 km (to France)

LED use phase

- Energy in use: Electricity, medium voltage {FR}| market for | Conseq, S

LED end of life

- Lamp: Used fluorescent lamp {GLO}| treatment of | Conseq, U – *Adaptations for 1 kg of lamp*:
    - o No emissions of mercury
    - o Hazardous waste, for underground deposit {GLO}| market for | Conseq, U = 0
    - o Glass cullet, from fluorescent lamps treatment {GLO}| market for | Conseq, U = 0
    - o Aluminium scrap, post-consumer {GLO}| market for | Conseq, U = 0.8 kg

   - electric arc furnace dust {RER}| market for electric arc furnace dust | Conseq, U= 0.2 kg
- Packaging: Waste paperboard {Europe without Switzerland}| market group for waste paperboard | Conseq, S

Impact assessment

Figure S2 presents the contribution analysis of the environmental impacts caused during the life cycle of 1 LED lamp. The results of Figure S2 represent Scenario 3, where europium is supplied from storage. The largest contributor to impacts is the manufacturing phase, of which the electronics (integrated circuit chip, printed wiring board, and transistor) generate the highest impacts and benefits. The environmental benefits generated at the end of life are due to the dataset that was chosen for the recycling of metals–represented by the recycling of aluminum.

Figure S3 demonstrates the sensitivity of the impacts of the demand for a LED lamp to the three different scenarios for the marginal supply of europium. The inventory is slightly affected by the three scenarios, due to the fact that the lamp uses yttrium oxide. During the production of yttrium oxide from the Longnan deposit, dysprosium and europium are produced as co-product, resulting in a decreased production of dysprosium by the Southeast Guangdong deposit. The co-production of europium from the latter deposit is higher than from the Longnan deposit. Therefore, the net result is a decreased supply of europium to the market.

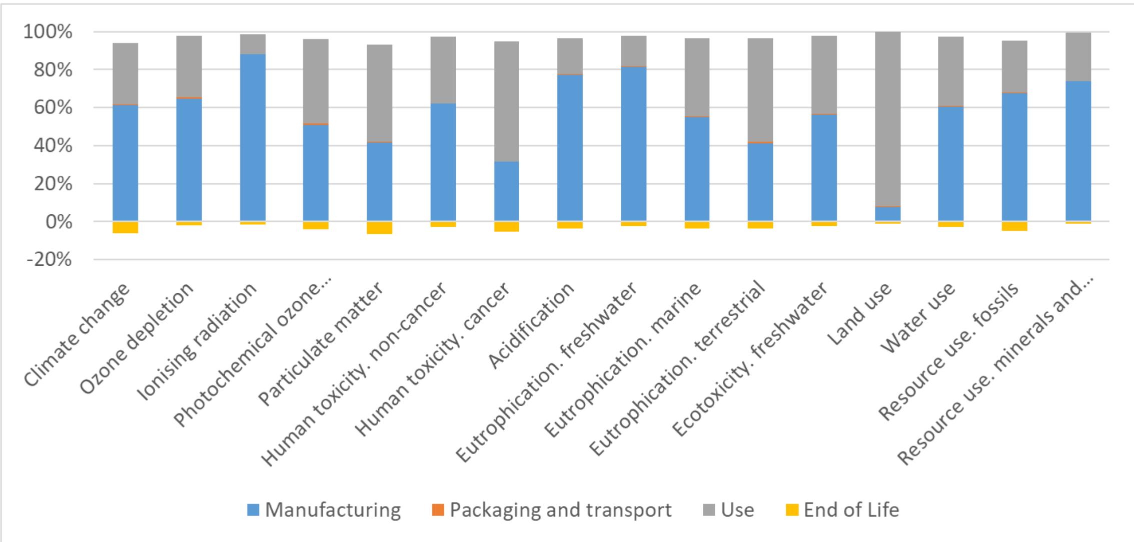

Figure S2. Contribution analysis of the life cycle of 1 LED lamp; europium is supplied from storage (Scenario 3).

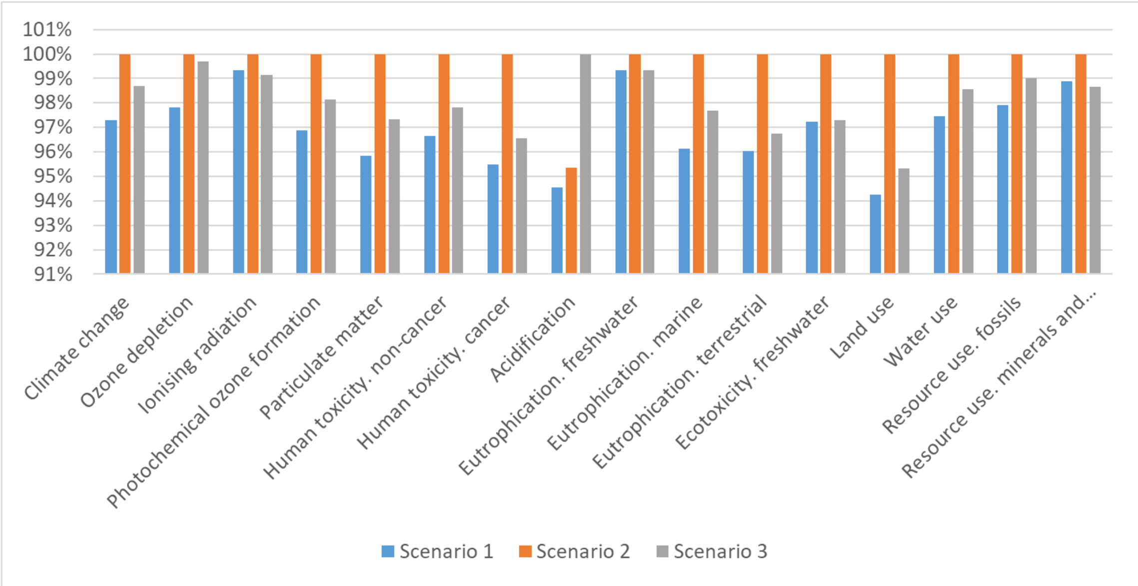

Figure S3. Relative environmental impacts caused by the demand for a LED lamp for the three scenarios for the marginal supply of europium. Scenario 1: marginal user is a CFL and CFLs only compete with LED lamps, Scenario 2: marginal user is a CFL and CFLs only compete with halogen lamps, Scenario 3: there is a surplus of europium and europium is supplied from storage.

LCI and impact assessment of a Halogen lamp

As stated above, the LCI for the halogen lamp is approximated by the LCI for the incandescent lamp from Scholand and Dillon. Their inventory is adapted as follows (for 1 lamp):

Halogen lamp production

- Filament—Tungsten: Tungsten concentrate {GLO}| market for tungsten concentrate | Conseq, S

Halogen lamp packaging and transport

- Packaging: Corrugated board box {RoW}| market for corrugated board box | Conseq, S
- Transport sea: 20.000 km (to France)

Halogen lamp use phase

- Energy in use: Electricity, medium voltage {FR}| market for | Conseq, S = 64.5 kWh

Halogen lamp end of life

- Lamp: Municipal solid waste {RoW}| market for | Conseq, S

- Packaging: Waste paperboard {Europe without Switzerland}| market group for waste paperboard | Conseq, S

Impact assessment

This inventory resulted in a distribution of environmental impacts among the life cycle phases as presented in Figure S4.

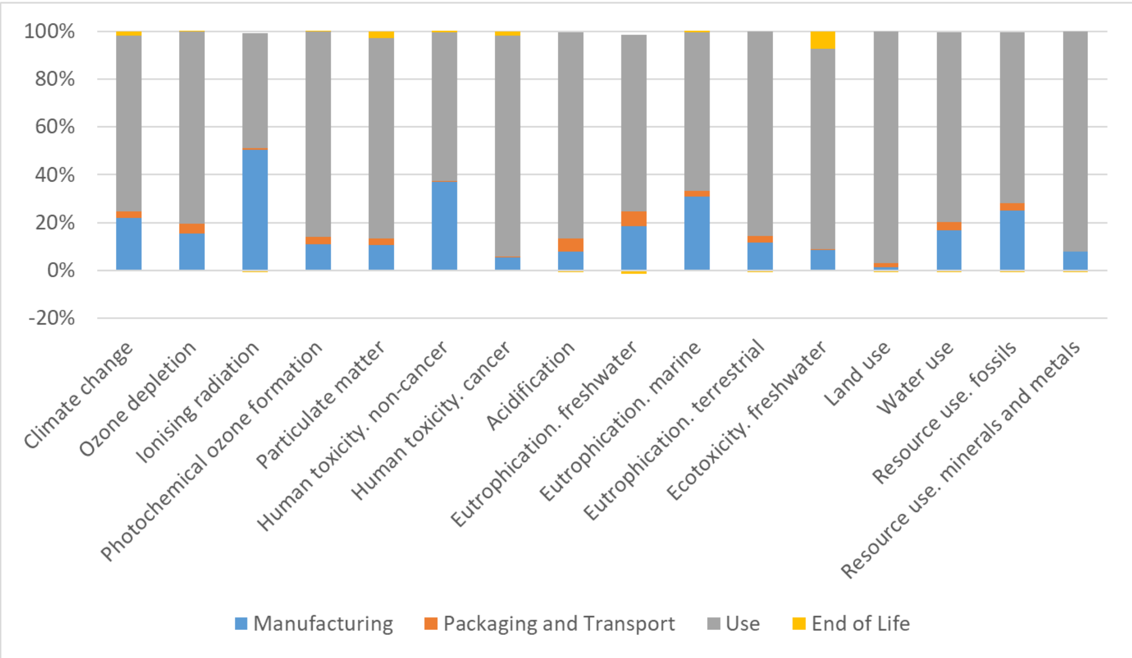

Figure S4. Contribution analysis of the life cycle of 1 halogen lamp.

LCI and impact assessment of a Fluorescent lamp

The following modifications are applied to the LCI of a fluorescent lamp from Scholand and Dillon.

CFL production

- "Yttrium Oxide" is modeled in more detail as follows:
    - Lanthanum oxide, from storage: 57 mg [18]
    - Cerium oxide, from storage: 135 mg [18]
    - Europium oxide, from marginal user: 30 mg [18]
    - Terbium oxide, from marginal user: 34 mg [18]
    - Yttrium oxide, from Longnan: 419 mg [18]
- Capacitor: 3.44 g (average weight of 0.086 g)
- Coil miniature: 50.4 mg (average weight of 16.8 mg)
- Diode: 1.28 g (average weight of 32 mg)
- Resistor SMD: 392 mg (average weight of 9.8 mg)

- Glass tube: 133 g (87% of the weight of a fluorescent lamp is glass [28])
- Copper: Copper-rich materials {GLO}| market for copper-rich materials | Conseq, S
- Aluminium oxide: Aluminium oxide, metallurgical {CN}| aluminium oxide production | Conseq, S

CFL packaging and transport

- Packaging: Corrugated board box {RoW}| market for corrugated board box | Conseq, S
- Transport sea: 20.000 km (to France)

CFL use phase

- Energy in use: Electricity, medium voltage {FR}| market for | Conseq, S

CFL end of life

- Lamp: New dataset created based on the inventory of [29] and information of [28]. It is assumed that mercury is not recycled [28].
- Packaging: Waste paperboard {Europe without Switzerland}| market group for waste paperboard | Conseq, S

Impact assessment

Figure S5 shows how the life cycle impacts of a CFL are built up, for the scenario in which europium is supplied from storage (Scenario 3). The impacts caused by the life cycle of a CFL (Figure S6) are more sensitive to the three scenarios for europium than the impacts of an LED lamp (Figure S3), due to the fact that more REEs are used in the CFL.

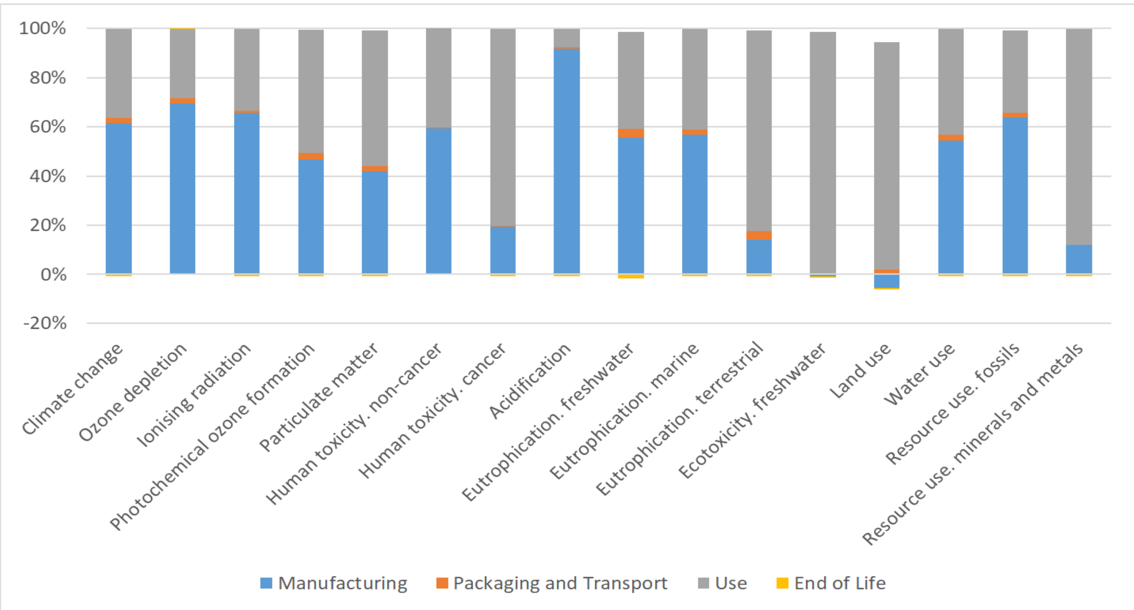

Figure S5. Contribution analysis of the life cycle of 1 CFL lamp; europium is supplied from storage (Scenario 3).

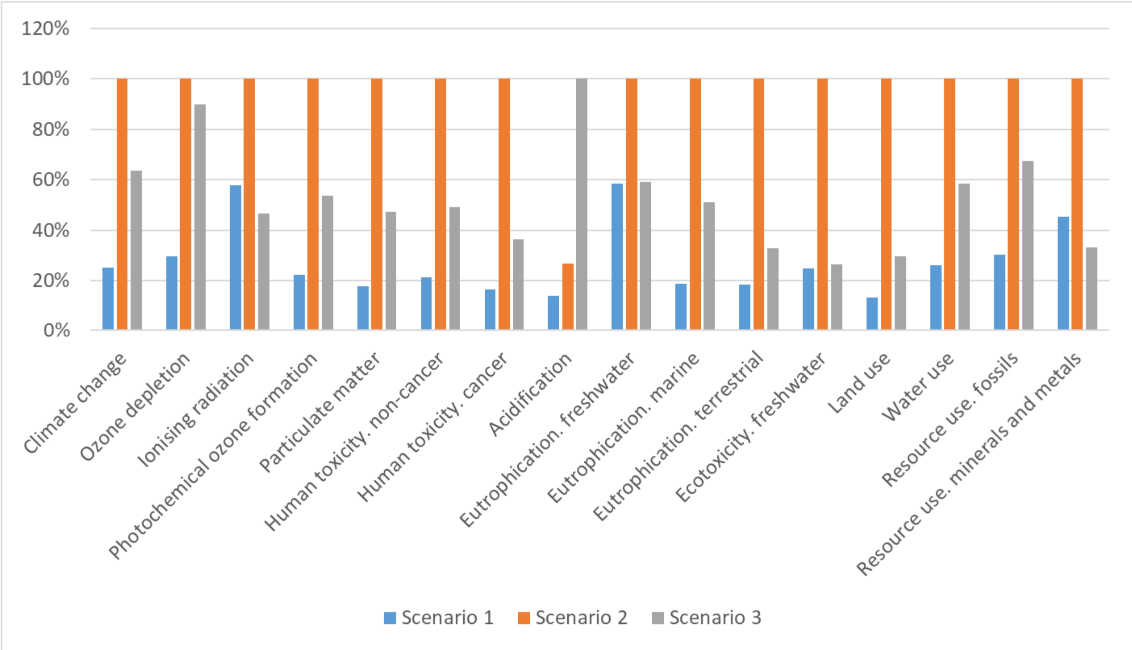

Figure S6. Relative environmental impacts caused by the demand for a CFL for the three scenarios for the marginal supply of europium. Scenario 1: the marginal user is a CFL and CFLs only compete with LED lamps, Scenario 2: the marginal user is a CFL and CFLs only compete with halogen lamps, Scenario 3: there is a surplus of europium and europium is supplied from storage.

Comparison of the three lamps

Figure S7–S9 present the relative environmental impacts of the three lamps for the three different scenarios for europium, respectively. The results are calculated for the functional unit of 6.6 Mlm-h, which is the lifetime light output of a fluorescent lamp (Table S10). It is interesting to notice that in Scenario 1 (Figure S7), the impacts of an LED lamp and a CFL are the same. This is explained as follows: europium oxide is used to make a CFL. By taking more europium from the market, less europium is available for the marginal user (also a CFL), resulting in an avoided production of CFLs as well as the avoided use and waste disposal of these lamps. Instead, there will be an increased production, use, and waste treatment of LED lamps. Therefore, the indirect effects of buying an additional CFL is the additional production, use, and disposal of (part of) an LED lamp, according to the output quantity of light of the two lamps. A similar effect takes place in Scenario 2 (Figure S8), although in this case, the alternative product for the CFL is the halogen lamp. In Scenario 3 (Figure S9) the use of europium does not lead to indirect effects. Therefore, the main difference between the lamps is caused by the differences in the use of electronics during the production phase and the electricity consumption during the use phase of the lamps.

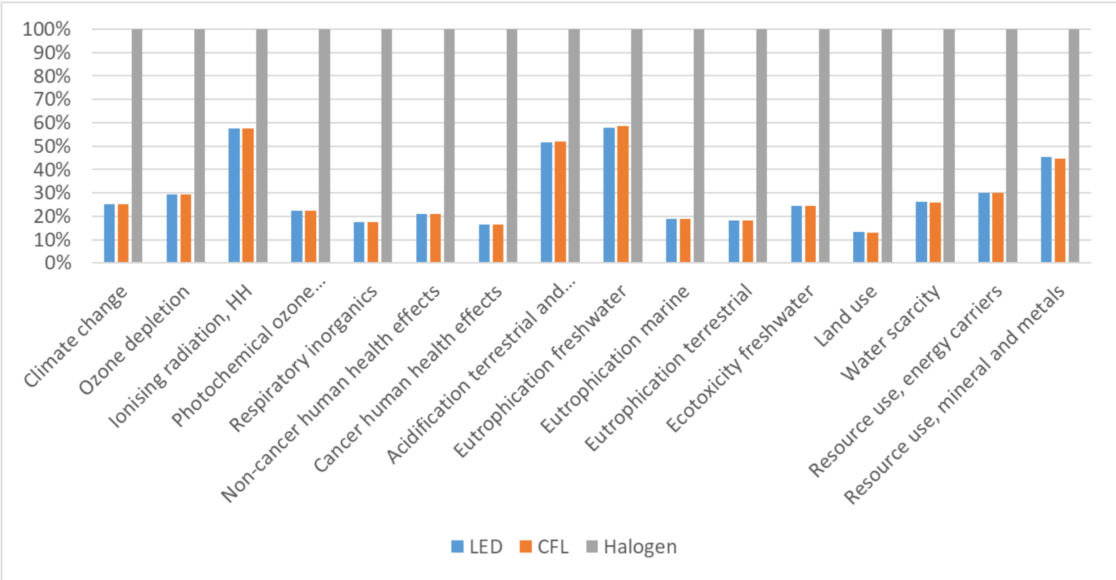

Figure S7. Relative environmental impacts caused by the functional unit (6.6 Mlm-h) for an LED, CFL, and halogen lamp in Scenario 1 (the marginal user of europium is a CFL, which competes with LEDs).

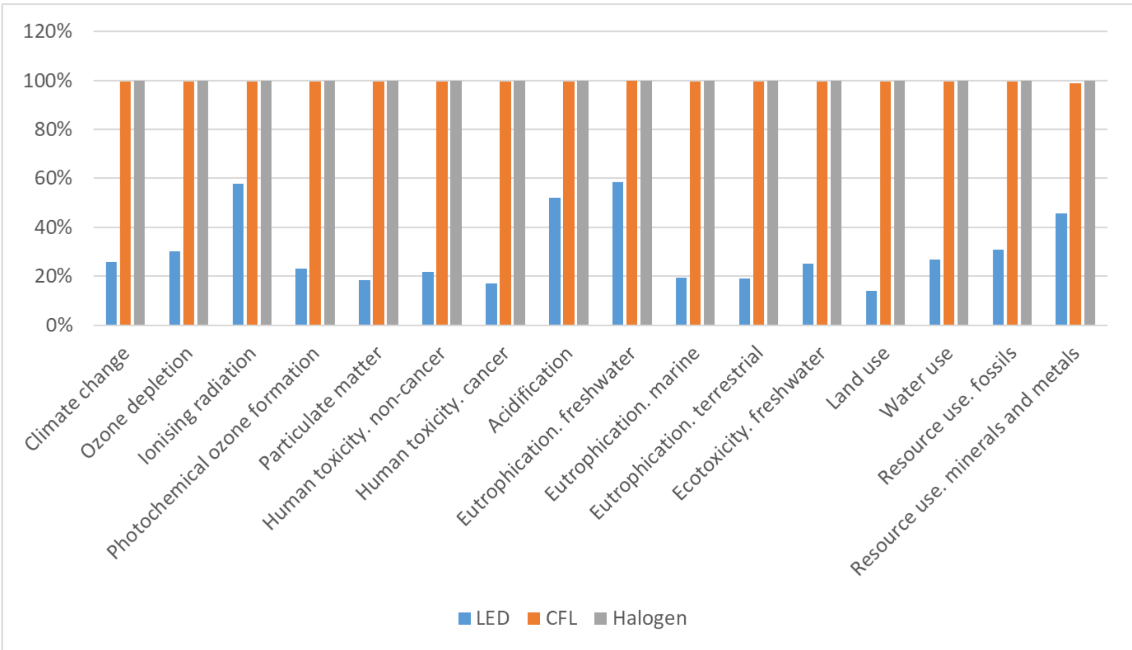

Figure S8. Relative environmental impacts caused by the functional unit (6.6 Mlm-h) for an LED, CFL, and halogen lamp in Scenario 2 (the marginal user of europium is a CFL, which competes with halogen lamps).

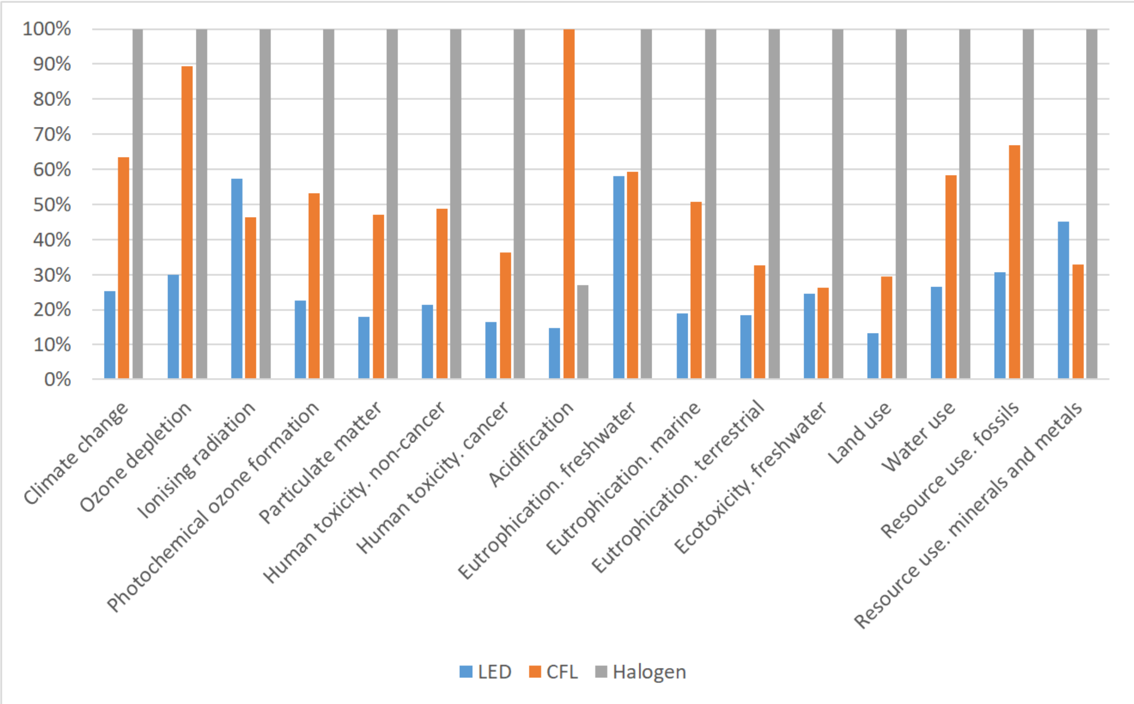

Figure S9. Relative environmental impacts caused by the functional unit (6.6 Mlm-h) for an LED, CFL, and halogen lamp in Scenario 3 (europium is supplied from storage).

References

1. Long KR, Van Gosen BS, Foley NK, et al. (2010) *The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective*. Dordrecht: Springer. https://doi.org/10.3133/sir20105220
2. Krishnamurthy N, Gupta CK (2016) *Extractive Metallurgy of Rare Earths*, 2 Ed., Boca Raton: CRC Press. https://doi.org/10.1201/b19055
3. Statista (2016) Rare Earth Oxides Base Prices 2009–2013. Available from: https://www.statista.com/statistics/449834/average-rare-earth-oxide-prices-globally/.
4. Consequential-LCA (2015) Further theory on marginal production costs. Available from: https://consequential-lca.org/.
5. Brown M, Eggert R (2017) Simulating producer responses to selected chinese rare earth policies. *Resour Policy* 55: 31–48. https://doi.org/10.1016/j.resourpol.2017.10.013
6. Consequential-LCA (2015) Further theory on normalising market trends. Available from: https://consequential-lca.org/.
7. Weidema BP, Ekvall T, Heijungs R (2009) Guidelines for application of deepened and broadened LCA—Deliverable D18 of work package 5 of the CALCAS project. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.628.948&rep=rep1&type=pdf.
8. Kätelhön A, von der Assen N, Suh S, et al. (2015) Industry-cost-curve approach for modeling the environmental impact of introducing new technologies in life cycle assessment. *Environ Sci Technol* 49: 7543–7551. https://doi.org/10.1021/es5056512

9. European Commission (2015) Report on critical raw materials for the EU—Critical raw materials profiles. Available from: https://ec.europa.eu/docsroom/documents/11911/attachments/1/translations.
10. USGS (2015) 2012 Minerals Yearbook—Rare Earths. Available from: https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/rare-earth/myb1-2012-raree.pdf.
11. Mining Technology (2016) Yangibana Rare Earth Project, Gascoyne Region. Available from: http://www.mining-technology.com/projects/yangibana-rare-earth-project-gascoyne-region/.
12. Northern Minerals (2011) BBY Rare Earth Conference 2011, Exploring High Value Heavy Rare Earths. Available from: https://www.asx.com.au/asxpdf/20110412/pdf/41xztx57qkwqhr.pdf.
13. GlobeNewswire (2015) Molycorp to move its mountain pass rare earth facility to 'care and maintenance' mode. Available from: http://globenewswire.com/news-release/2015/08/26/763530/0/en/Molycorp-to-Move-Its-Mountain-Pass-Rare-Earth-Facility-to-Care-and-Maintenance-Mode.html.
14. Northern Minerals (2015) ASX Announcement, 100% ownership of John Galt Project secured. Available from: https://www.asx.com.au/asxpdf/20150619/pdf/42z8y0jc714lw9.pdf.
15. Lynas Corporation LTD (2016) FY16 Financial Report. Available from: https://www.lynascorp.com/Shared Documents/Investors and media/Reporting Centre/Annual reports/2016/160929 FY16 Financial Report 1548914.pdf.
16. Statista (2016) Neodymium oxide price worldwide from 2009 to 2025. Available from: https://www.statista.com/statistics/450152/global-reo-neodymium-oxide-price-forecast/.
17. Statista (2016) Lanthanum oxide price worldwide from 2009 to 2025. Available from: https://www.statista.com/statistics/450139/global-reo-lanthanum-oxide-price-forecast/.
18. Chu S (2011) *Critical Materials Strategy*, Collingdale: DIANE Publishing.
19. Leveque A, Maestro P (1993) Terres rares. Available from: https://www.google.fr/books/edition/Terres_Rares/zhqex2_Wes0C?hl=en&gbpv=0.
20. Wang L, Huang X, Yu Y, et al. (2013) Eliminating ammonia emissions during rare earth separation through control of equilibrium acidity in a HEH(EHP)-Cl system. *Green Chem* 15: 1889. https://doi.org/10.1039/c3gc40470f
21. Gupta CKK, Krishnamurthy N (2005) *Extractive Metallurgy of Rare Earths*, Boca Raton: CRC Press.
22. Binnemans K (2014) Economics of rare earths: the balance problem, *Proceedings of the 1st European Rare Earth Resources Conference (ERES 2014)*, 37–46.
23. Nassar NT (2015) Limitations to elemental substitution as exemplified by the platinum-group metals. *Green Chem* 17: 2226–2235. https://doi.org/10.1039/C4GC02197E
24. Scholand M, Dillon H (2013) *Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products—Part 2: LED Manufacturing and Performance*, Richland: U.S. Department of Energy. https://doi.org/10.2172/1044508
25. Navigant Consulting Inc. (2012) Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products—Part I: Review of the Life-Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps. Available from: https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_LED_Lifecycle_Report.pdf.

26. Grandell L, Lehtilä A, Kivinen M, et al. (2016) Role of critical metals in the future markets of clean energy technologies. *Renew Energy* 95: 53–62. https://doi.org/10.1016/j.renene.2016.03.102
27. Kim MJ, Park JH, Lee KY, et al. (2014) Cerium-doped yttrium aluminum garnet hollow shell phosphors synthesized via the Kirkendall effect. *ACS Appl Mater Interfaces* 6: 1145–1151. https://doi.org/10.1021/am404809s
28. Récylum (2018) Recyclage des ampoules: pourquoi, comment les recycler? Available from: https://www.recylum.com/particuliers/recyclage-des-lampes/.
29. Tan Q, Song Q, Li J (2015) The environmental performance of fluorescent lamps in China, assessed with the LCA method. *Int J Life Cycle Assess* 20: 807–818. https://doi.org/10.1007/s11367-015-0870-2